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METEOROLOGICAL CONDITIONS AFFECTING RENEWABLE ENERGY

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ACADEMIC DISSERTATION in meteorology

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Meteorological conditions affecting renewable energy

Abstract

Synoptic situation and different meteorological phenomena can highly affect renewable energy production. Investigating different phenomena will give new information on the occurrence and characteristics of specific phenomena and their impacts on renewable energy applications. Different observational data sets and numerical models can be widely used in different phases of renewable energy projects; from planning of the project to help with the operation and the maintenance of the existing wind or solar field.

In this thesis a meteorological phenomena, a low-level jet, is investigated. Thesis comprises analysis of the climatological occurrence of low-level jets, their characteristics and forcing mechanisms, as well as numerical model capability to capture the phenomena. In addition, solar radiation forecasts obtained from the operational numerical weather prediction model are evaluated and the role of cloud cover forecast skill in solar radiation forecast error is investigated. Long data sets of observational data: mainly Doppler wind lidar, ceilometer, and solar radiation observations, are used, in addition to reanalysis and operational numerical weather prediction model data.

A low-level jet is a wind phenomenon that can affect wind energy production. Nighttime low-level jets are a commonly known boundary-layer phenomenon occurring during stably stratified conditions over flat terrain. In this thesis, new information on the occurrence, characteristics, and forcing mechanisms of a low-level jet was gained in different conditions: in Northern Hemisphere mid-latitude and polar regions based on reanalysis data and at two different sites in Finland and Germany based on long-term Doppler lidar observations. The low-level jet identification algorithms developed in these studies can be used to repeat the studies by using different models covering different areas or at any site operating a Doppler lidar. The low-level jet identification algorithm for Doppler lidar data can also be applied to operationally detect low-level jets, which is useful information for example from wind energy point-of-view.

Solar radiation and cloud cover forecasts were evaluated at one site in Finland based on long time-series of solar radiation and ceilometer observations. The role of cloud cover forecast in solar radiation forecast error is investigated. The solar radiation and cloud cover forecasts were obtained from operational numerical weather prediction model that can be used to predict the expected power production at solar field day-ahead. It was found that there is a positive bias in the forecast incoming solar radiation even if the cloud cover forecast is correct. The study can guide model improvements as the bias is likely due to underestimation in the forecast cloud liquid water content or incorrect representation of cloud optical properties. The methods created in this study can be applied to hundreds of sites globally. In addition, the algorithms developed in this study can be further used in different applications in the field of renewable energy, for example to detect potential in-cloud icing conditions.

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Tekijä
Minttu Tuononen

Nimike
Meteorologisten ilmiöiden vaikutuksista uusiutuvaan energiaan

Tiivistelmä

Vallitseva säätila ja paikalliset meteorologiset ilmiöt voivat selvästi vaikuttaa tietyllä alueella havaittavaan tuulisuuteen ja pilvisyyteen ja näin ollen mahdollisen tuuli- tai aurinkoenergian tuotantoon. Meteorologisia ilmiöitä tutkimalla saadaan lisätietoa niiden esiintyvyydestä ja ominaisuuksista, ja tätä tietoa voidaan edelleen käyttää ilmiöiden vaikutusten arviointiin uusiutuvan energian näkökulmasta. Erilaisia meteorologisia havaintoaineistoja ja numeerisia malleja voidaan hyödyntää uusiutuvan energian käyttöön tähtäävän projektin eri vaiheissa mahdollisen uuden tuuli- tai aurinkovoimalan suunnittelusta olemassa olevan voimalan operatiivisen toiminnan tukemiseen.

Tässä väitöskirjatutkimuksessa on tarkasteltu uusiutuvan energian tuotantoon vaikuttavan meteorologisen ilmiön, alatroposfäärin suihkuvirtauksen, esiintyvyyttä, ominaisuuksia, syntymekanismeja sekä numeerisen mallin kyvykkyyttä ilmiön mallintamisessa. Lisäksi tutkittiin operatiivisen sääennustusmallin kyvykkyyttä auringonsäteilyn ja pilvisyyden ennustamisessa sekä pilvisyysennusteiden roolia säteilyennusteiden ennustevirheissä. Väitöskirjassa on käytetty pitkiä meteorologisia havaintosarjoja: Doppler lidar -tuulimittauksia, ceilometrillä tuotettuja pilvisyysmittauksia, säteilyhavaintoja, sekä numeerilla malleilla tuotettuja aineistoja: uusanalyysiä ja operatiivisen sääennustusmallin tuottamia säteily- ja pilvisyysennusteita.

Alatroposfäärin suihkuvirtaus on tuuli-ilmiö, joka on yleisesti tunnettu erityisesti stabiilin yöllisen rajakerroksen tilanteessa. Ilmiötä on tämän väitöskirjan osatutkimuksissa tutkittu numeerisen mallin ja laajan havaintoaineiston yhdistelmän, uusanalyysin, perusteella pohjoisen pallonpuoliskon keskileveys- ja napa-alueella, sekä kahdella eri mittausasemalla Doppler lidar -tuulimittausten perusteella. Tutkimuksissa havaittiin, että alatroposfäärin suihkuvirtaus esiintyy usein modernien tuuliturbiinien vaikutusalueella lisäten turbulenssin aiheuttamaa stressiä, sekä paikallisesti alueilla, joilla ilmiötä ei ole aiemmin tutkittu. Tutkimuksissa kehitettyjen algoritmien avulla alatroposfäärin suihkuvirtauksien tutkiminen ja operatiivinen havainnoiminen on mahdollista aiempaa laajemmassa mittakaavassa Doppler lidar -havaintoja käyttäen.

Pilvisyysennusteiden vaikutusta auringonsäteilyennusteisiin tutkittiin käyttämällä pitkiä havaintosarjoja pilvisyydestä ja auringonsäteilystä, ja vertaamalla havaintoja operatiivisiin pilvisyys- ja säteilyennusteisiin. Tutkimuksessa selvitettiin kuinka hyvin säteily- ja pilvisyysennusteet toteutuvat yhdellä mittausasemalla Suomessa. Oikein ennustetuissa pilvisyystilanteisssa havaittiin positiivinen ennustevirhe maan pinnalle saapuvassa auringonsäteilyssä. Todennäköinen syy tähän positiiviseen säteilyennustevirheeseen liittyy pilvien vesisisällön aliarvioimiseen tai heikkouksiin pilvien optisten ominaisuuksien mallintamisessa. Tutkimuksessa kehitettyjen menetelmien avulla on mahdollista laajentaa tutkimus koskemaan satoja mittauasemia ympäri maailmaa.

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Preface

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Minttu Tuononen
Helsinki, April 2019

Contents

List of original publications

I Tuononen, M., Sinclair, V. A., and Vihma, T., 2015: A climatology of low-level jets in the mid-latitudes and polar regions of the Northern Hemisphere. *Atmospheric Science Letters*, **16**, 492–499, doi:10.1002/asl.587

II Tuononen, M., O'Connor, E. J., Sinclair, V. A., and Vakkari, V., 2017: Low-level jets over Utö, Finland, based on Doppler lidar observations. *Journal of Applied Meteorology and Climatology*, **56**, 2577–2594, doi:10.1175/JAMC-D-16-0411.1

III Marke, T., Crewell, S., Schemann, V., Schween, J. H., and Tuononen, M., 2018: Long-term observations and high-resolution modeling of midlatitude nocturnal boundary layer processes connected to low-level jets. *Journal of Applied Meteorology and Climatology*, **57**, 1155–1170, doi:10.1175/JAMC-D-17-0341.1

IV Tuononen, M., O'Connor, E.J., Sinclair, V.A., 2019: Evaluating solar radiation forecast uncertainty, *Atmospheric Chemistry and Physics*, **19**, 1985–2000, doi:10.5194/acp-19-1985-2019

List of acronyms

ASR Arctic System Reanalysis

DBS Doppler Beam Swinging

ECMWF European Center for Medium Range Weather Forecasts

DHI Diffuse Horizontal Irradiance

DNI Direct Normal Irradiance

GOS Global Observing System

GHI Global Horizontal Irradiance

IFS Integrated Forecast System

IPCC Intergovernmental Panel on Climate Change

IRENA International Renewable Energy Agency

LES Large-Eddy Simulation

LIDAR Light Detection and Ranging

LLJ Low-Level Jet

LWP Liquid Water Path

NWP Numerical Weather Prediction

ME Mean Error

TOA Top Of Atmosphere

SODAR Sound Detection and Ranging

VAD Velocity Azimuthal Display

1. Introduction

Climate change has increased the attention towards renewable energy. The Paris agreement set an ambitious goal to the world's nations, which is to limit the global mean 2 m temperature increase to well below 1.5°C, thus pursuing the path of effectively limiting greenhouse gas emissions. According to the Intergovernmental Panel on Climate Change (IPCC), the global net anthropogenic CO_2 emissions should reach net-zero around 2050 to limit the global mean warming at the surface to 1.5°C above pre-industrial levels (IPCC, 2018). To reach the net-zero level, the use of fossil fuels should be substituted with cleaner energy production, including renewable energy sources.

After hydropower, the main renewable energy sources are wind and solar (IRENA, 2019). Wind is converted to electricity by wind turbines where the kinetic energy of wind (air flow) is turned to mechanical power by the rotating wind turbine blades and furthermore to electricity by the generator of the wind turbine. Solar energy, in turn, is converted to electricity by solar panels (photovoltaic effect) or heat by concentrating the sunlight with mirrors or lenses. According to the International Renewable Energy Agency (IRENA), the installed wind and solar energy capacities globally at the end of 2018 were 564 GW and 486 GW, respectively, with consistently growing trend over time (IRENA, 2019).

Both wind and solar resources are highly variable and dependent on geographical location, season, time-of-day and weather. Atmospheric science is a crucial scientific field when discussing wind and solar energy. It includes atmospheric physics and chemistry, climatology and meteorology – all being important and closely related to each other when trying to understand the highly variable nature of wind and solar resources. Wind and solar energy resources can be estimated by using meteorological knowledge, meteorological observations and numerical weather prediction models. In addition, the understanding of meteorological conditions and phenomena helps with estimating weather-related risks affecting renewable energy projects, comprising both safety and profitability aspects.

The focus of this thesis is on renewable energy meteorology. The general aim of this thesis has been to increase our understanding on how different meteorological conditions affect wind and solar energy. This general aim is addressed in four research articles, through more specific research questions and aims:

1. **Low-level jets are a potentially valuable wind resource but they may also harm the wind turbines. How well can we observe and characterise low-level jets, and can we map this resource using reanalysis data?**
   In papers I-III, the aim was to derive a climatology of low-level jets based

on reanalysis data (paper I) and Doppler lidar observations (papers II, III). Automated algorithms were developed and applied to data in papers I, II, and III to objectively identify low-level jets from gridded reanalysis output, and high temporal and vertical resolution Doppler wind lidar observations, also enabling real-time detection. The occurrence and characteristics of low-level jets were investigated in papers I-III.

2. **The amount of clouds and incoming solar radiation are highly variable in nature. How well can operational numerical weather prediction model predict clouds and incoming solar radiation at the surface?**
   In paper IV algorithms were created for ceilometer data to detect liquid cloud layers, ice clouds, precipitation and fog. The aim was to evaluate the operational short-term cloud cover and solar radiation forecasts by comparing day-ahead forecasts of cloud cover and surface solar radiation against ceilometer and pyranometer observations.

3. **How observational systems can help numerical weather prediction model development?**
   The aim has been to create automated algorithms that are easily applicable to different sites operating similar instruments. A detailed comparison of model output to quality-controlled observations are needed for model evaluation, and furthermore model development. The model evaluation may reveal deficiencies of a model's capability to represent specific conditions accurately and these aspects are discussed in all papers.

The introduction to this thesis is structured as follows: in section 2 the background of this thesis is discussed. Data and methods used in this thesis are briefly described in section 3 followed by the main results in section 4. Section 5 contains the review of papers and author's contribution. Finally, the discussion and conclusions are presented in section 6. The four published papers are printed in order of their publication at the end of this thesis.

2. Background

2.1. Renewable energy meteorology

The energy received from the sun drives the Earth's renewable energy sources. The amount of solar radiation received at the top of the atmosphere depends on the Earth's tilt towards the sun, and in addition, the amount of solar energy received at the surface depends on the solar radiation absorbed and reflected by the clouds and the atmospheric gases and aerosols. The uneven distribution of sunlight at the Earth's surface and the rotation of the Earth result in differences in atmospheric pressure and consequently large-scale atmospheric circulation. Although windiness depends fundamentally on the large-scale circulation, local effects, such as topography and coastal effects also affect the wind field and are important in determining the local wind resources.

As renewable energy resources are highly variable in nature, it is crucial for renewable energy applications to determine and understand the local wind and solar resources and how different meteorological conditions affect them. Long-term variability (yearly and monthly variation) must be determined in the planning phase of a renewable energy project and short-term variability (diurnal and hourly variation) must be known for the operational purposes. These can be obtained by using different meteorological data: long-term meteorological observations and reanalyses for long-term variability, and real-time observations and forecast models for short-term variability.

There are different meteorological conditions that affect the available amount of wind and solar resources. For example, the increased wind speed due to favorable atmospheric conditions may ramp up the wind energy production locally. Similarly, clear-sky periods due to high pressure situations are favorable conditions for solar energy production resulting in more available solar energy. In addition, different meteorological conditions, such as atmospheric icing and increased wind shear and turbulence, may harm the equipment, for example decreasing the life time of wind turbines. Therefore, the occurrence and characteristics of meteorological phenomena affecting renewable energy is crucial to understand before the design and construction of a new renewable energy project. Meteorological conditions and different phenomena determine and influence the selection of the site location, what equipment to be used (such as turbine type), and layout of the project, but also the operation of the existing wind or solar site.

2.2. Meteorological data in renewable energy

Different meteorological data sets can be widely utilized in different phases of the renewable energy projects. For instance, accurate site assessment is required before building a wind or solar farm to ensure the profitability of the project. In the operational phase of the existing wind or solar energy site, accurate wind or solar radiation forecasts and real-time observations are requested. Therefore, a range of different data sets are required. This includes gridded meteorological data which resolve large-scale phenomena as well as site specific observations of relevant meteorological variables. The optimum data set for each application highly depends on the application, for example on the required accuracy and desired length of the data set.

Observations

The Global Observing System (GOS), guided and coordinated by the World Meteorological Organization, and operated on a national and international level, provides an extensive amount of meteorological observations of the atmosphere and ocean surface. Every day, billions of observations – including data from traditional in-situ point observations, single-profile measurements (radiosoundings and ground-based remote sensing), more complex profiling (cloud radars and weather radars), satellite-based remote sensing, ships and aircraft – are gathered, stored and used. Meteorological observations play a fundamental role in Numerical Weather Prediction (NWP) as they are used in determining the initial condition of the atmosphere that is necessary for obtaining accurate forecasts ahead in time. Meteorological observations are also used in NWP model development, and in monitoring the real-time conditions and obtaining advisory and warning systems of weather-related conditions.

Different observational data sets are used across a wide range of renewable energy applications. For example the accurate resource assessment of incoming solar radiation at a specific site requires at least one year of quality-controlled solar radiation measurements to determine the seasonal variation. However, preferably, several years of observations should be used to understand the year-to-year variation. Solar radiation at the surface is typically measured with in-situ pyranometers and pyrheliometers, to obtain all of the solar radiation components usable in solar energy applications: Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI).

The same requirement for long observational data sets described above for solar energy applications applies to wind energy applications. Wind measurements are conventionally done with wind sensors located at different heights on a meteorological mast, using different in-situ wind sensors: cup anemometers and wind vanes or sonic anemometers. However, the wind energy industry is moving towards the use of ground-based remote sensing instruments to obtain wind profile measurements with higher temporal and vertical resolution, especially using Light Detection and Ranging (lidar) and Sound Detection and Ranging (sodar) instruments. In addition to improved vertical resolution over the appropriate height range of modern wind turbine, the lidar and sodar instruments are easy to relocate, which enables measurements from several locations, for example within the site. This is a huge advantage compared to conventional meteorological masts that are deployed in one location only and are in practise unprofitable to relocate.

Doppler lidars have become very popular in the field of wind energy (Banta et al., 2002; Pichugina et al., 2012; Hasager et al., 2013; Banta et al., 2013). The basic principle of a Doppler wind lidar in retrieving the wind profile is the detection of the movement of aerosol particles that are transported by the air flow. The movement detection relies on measuring the Doppler shift (shift in received versus transmitted laser frequency) when the transmitted laser signal is backscattered from the moving particles. One beam direction gives the line-of-sight velocity information and the wind speed and direction (three-dimensional quantity) is obtained by transmitting a laser beam in at least three different directions to resolve the three-dimensional wind vector. This calculation assumes horizontal homogeneity in the scanning volume. The wind field is usually not horizontally homogeneous which affects the data quality and the detection of moving particles requires aerosols to follow. The latter is a problem in clean conditions when there is not enough signal to retrieve the wind information. In addition, it should be kept in mind that the lidar signal attenuates in thick cloud layers, and no information is available above. These measurement principles result in limitations in terms of data availability.

Doppler lidars can obtain the wind profile by using different scanning schemes (Werner, 2005), for example using Velocity Azimuthal Display (VAD) or Doppler Beam Swinging (DBS) scans. The measurement volume and the vertical resolution of the wind profile is determined by the scan settings used, such as the elevation angle of the laser beam. The aspects of the desired vertical resolution, temporal resolution, data quality and measurement volume should be taken into account when determining the optimal scanning pattern of the instrument for each application.

The information obtained by transmitting a laser pulse and receiving the backscattered signal is also used in other meteorological applications than wind profile measurements. Cloud profiling can be done by using a simpler lidar system, a ceilometer. The detection of clouds with lidar ceilometer requires a light pulse pointed only into one direction, and it does not require Doppler shift detection. The cloud measurement relies on receiving the backscattered laser signal from the cloud droplets and ice crystals. Ceilometers can also be used to detect the aerosol layers (and to obtain mixing layer height; Wiegner et al., 2014) and precipitation. Traditionally ceilometers are used at airports to detect the cloud base height and sky condition information, and therefore there is a dense network of ceilometers distributed around the world (Illingworth et al., 2019). This is a notable benefit compared to other cloud profiling instruments (such as cloud radars, research lidars) which are not as densely distributed. The limitation of ceilometers is that they usually see only up to the lowest liquid cloud layer, as the lidar signal attenuates rapidly when passing through a liquid cloud.

Obtaining profile data has advantages in the renewable energy field. For the wind energy industry, it is beneficial to obtain wind speed profiles up to several hundred meters above the surface, as the modern commercial wind turbine rotor diameter and hub height now exceed 160 m. For solar energy purposes, and especially observing clouds, profiling instruments (or a combination of them) are the most useful as more information on the cloud properties, such as presence of liquid cloud layers, can be obtained when using the attenuated backscatter profile information compared to traditional cloud base height and sky condition retrievals (Illingworth et al., 2007).

Numerical models

For the general public, the most well-known product from the field of meteorology is a weather forecast, produced by NWP models. NWP models are mathematical models where the evolution of the atmospheric state can be predicted through resolving the equations representing the atmospheric dynamic and thermodynamic state, and parameterizating the physical processes too small to be resolved, ahead in time. Dynamic and thermodynamic equations solve the atmospheric flow and thermodynamic state, whereas physical parameterizations are used to derive radiation, clouds, convection, turbulence, and other sub-grid size phenomena. NWP models can be used to produce a range of different forecasts and simulations from nowcasting to seasonal predictions and over a range of spatial scales from regional to global. For example, the European Centre for Medium-Range Weather Forecasts (ECMWF), produces medium-range forecasts twice a day with a forecast horizon of up to 15 days, extended-range forecasts twice a week up to 46 days and long-range forecasts once a month up to 7 months. There are global forecasting systems, such as the ECMWF Integrated Forecast System (IFS) model, and higher resolution regional NWP models covering a limited area, such as HIRLAM and HARMONIE. The grid resolution can vary considerably between different NWP models. For example, the spatial resolution of the operational IFS model is approximately 9 km and in the vertical there are 137 levels from ground to the top of atmosphere whereas HARMONIE-AROME has 2.5 km horizontal resolution and 65 vertical levels.

NWP models use real-time observations gathered through GOS to determine the most realistic atmospheric state in a procedure called data assimilation. In this step, the model initial state is represented relying on the real-time measurements and given to the equations solving the atmospheric dynamic and thermodynamic state, and to forecast ahead in time. In the case of ensemble forecasts, the initial state is perturbed to get slightly different initial states for each ensemble member. The spread between the ensemble members can then be used to estimate the uncertainty of the prediction (probabilistic forecast). The deterministic forecast does not itself include any information on the probability. NWP models resolve the evolution of large-scale circulation, and synoptic and mesoscale features, i.e. they resolve the atmospheric flow and movements of frontal systems. However, they may not always capture small-scale phenomena correctly, such as coastal effects, due to the deficiencies in resolution or incorrect parameterization, resulting in decreased skill in predicting certain meteorological conditions. Overall, the skill of NWP models has been considerably improved with the increase in computational power allowing for a better grid resolution, improved parameterizations and the amount of real-time data (mainly satellite data) assimilated in to the model (Bauer et al., 2015).

In the field of renewable energy, NWP models can be used for example to predict the amount of incoming solar radiation for the day-ahead to guide the solar energy markets. Similarly, wind speed forecasts are used to predict the potential wind energy production over different time windows. Therefore, there are certain needs for the accuracy of the NWP model also in the renewable energy perspective.

Large-Eddy Simulation (LES) models are high-resolution numerical models that are used to resolve the turbulent flow with a range of time and length scales. In comparison to LES models, NWP models do not directly resolve the turbulent eddies, as the turbulent motions are parameterized. LES models can be used for research purposes to investigate different phenomena in detail over a certain area, for example in boundary-layer studies. However, as LES models require very high resolution in time and space, they are computationally extremely expensive. Therefore, LES models are not suitable for operational use. The information gained from LES can provide valuable information to deeply understand the physical processes that are acting, such as forcing mechanisms of a low-level jets or structure of clouds smaller than usual grid size.

Reanalysis

Reanalysis is a combination of meteorological observations and a numerical model, resulting in gridded data set covering areas from regional to global scales and typically spanning historical time windows of several decades. Reanalysis is produced by using a NWP model and adding the information content of historical meteorological observations in the data assimilation process. Thus, running the NWP model over times when meteorological observations are available, and repeating the data assimilation process with all of the available observations for each time step and grid point, the resulting data set is seen as the best estimate of the state of the atmosphere in gridded form, possibly spanning the whole globe from ground to the top-of-atmosphere over tens of years. One of the advantages of reanalysis data is that they are produced based on the latest NWP model cycle (at the production time), thus the aim is to use the most skillful model for the whole historical time window, and incorporate more observations than are available for the operational forecast. Therefore, the reanalysis data is also free of changes due to NWP model development, i.e. increase in model's skill over time.

There are different reanalysis data sets covering the whole globe (e.g. ERA5, ERA-Interim, MERRA) and some limited area (e.g. COSMO-REA, ASR). The single-level and model-level variables can be obtained from any grid point and over a large time window, therefore enabling e.g. climatological studies investigating seasonal variations or trend analysis. The horizontal resolution may vary considerably between different data sets, usually being coarser for global data sets. For example, the newest global reanalysis dataset ERA5 by ECMWF (ERA5, 2019) has spatial resolution of 30 km with 137 vertical levels, and the newer version of ASR (ASRv2, Bromwich et al., 2018), covering limited area, has 15 km spatial resolution with 71 model levels. Most of the global reanalysis datasets span multiple decades, usually starting from 1979 (or before) to almost real-time with temporal resolutions varying from hourly to 3-hourly or coarser. Additionally, many of these data sets are freely available, which makes them easily accessible for wide usage.

In renewable energy applications, reanalysis can be used to estimate the incoming solar radiation at the surface, wind speed at different levels, as well as investigating relevant meteorological phenomena derived from the reanalysis output. Reanalysis data are useful for a wide range of applications; however, these data may not be suitable for detailed investigation of a phenomenon at a certain location due to the deficiencies in the temporal and spatial resolution.

Algorithms

An algorithm is a recipe or a decision tree which describes a process in a mathematical or logical form. Usually algorithms contain separate tasks that are solved by a computer. For example, a simple algorithm could find the number of hours when the averaged wind speed exceeds 10 $\mathrm{m\,s^{-1}}$ over the past two years. The power of algorithms is that they can process large sets of information and the results should, in principle, be objective as they can strictly follow the given relations or rules without suffering from human errors, therefore lacking subjective bias. Algorithms can easily process massive amounts of data with complicated relations, which would be an impossible task for a human to analyse manually. Objectivity and capability to efficiently handle massive amounts of data with complicated connections are desirable features, for example, when the aim is to identify a certain meteorological condition by using multiple years of meteorological data.

At wind farms, the real-time wind measurements from the wind turbine nacelles are used to determine the estimated power production and to detect faulty conditions, e.g. due to atmospheric icing, by using simple algorithms. Other meteorological phenomena can be automatically identified based on the real-time observations with a set of rules by using more complicated algorithms, such as identification of a low-level jet by using wind profile observations or estimation of conditions causing wind turbine icing by using a combined information from different observational data sources and/or forecast data.

In contrast to real-time monitoring, algorithms can also be used to analyse historical data. When investigating over several years, the automated identification of a particular phenomenon or process is usually necessary. With algorithms applied to historical data (observations or model), it is possible to investigate the climatological behaviour of the feature of interest. This is desirable, for example, when estimating the impacts of certain phenomena on a renewable energy project – it is beneficial to understand the occurrence of hazardous phenomena when estimating the possible stresses that will be expected by the structures, for example wind turbines. In these cases, it is again required that large amounts of data can be objectively analysed.

Model evaluation

NWP models may not always represent the atmospheric conditions and different phenomena accurately. Hence, if only relying on model data, any inaccuracy in estimating turbulence would likely impact the estimated wind resource or the expected life-time of the wind turbines. As numerical models are needed for estimating renewable energy resources and other weather-related impacts, and for forecasting the amount of expected power production one day-ahead at any location, it is vital to know how accurate the NWP model is.

Different meteorological observations are used for model evaluation at the location of available measurement data. Especially long time series of observational data, with possible algorithms applied to investigate certain phenomena, are used for investigating the model's performance. To determine the accuracy of the model, the model must be systematically compared against observations by using large amount of data. Comparing model output with observations is not always a simple task, as the nature of model and observational data differ. NWP output is usually a representation of a condition in a grid-space, thus the forecast values represent averaged or instantaneous conditions over a certain area or volume. On the other hand, observations may be a point measurement (for example traditional solar radiation observations by a pyranometer) or a measurement over a certain area (such as satellite-derived solar radiation data).

The accuracy of NWP models can be analysed by using a wide range of error metrics and skill scores (Casati et al., 2008). These represent the differences between the observations and forecast data, thus describing how well the forecast model is representing the real (observed) conditions. The model's skill in forecasting a certain condition may vary diurnally, seasonally or based on location. For example, it is known that a typical model's resolution may not be high enough to produce some local effects, such as coastal or mountainous effects, and that small-scale phenomena are harder to predict compared to large-scale effects. Some conditions have diurnal and seasonal variability and if the models have deficiencies in representing these conditions accurately, this may result in diurnal and/or seasonal variations in model's skill to predict a certain phenomenon.

2.3. Low-level jets, clouds and solar radiation

In this thesis, the focus has been on low-level jets that potentially affect wind energy, and on forecasts of low- and mid-level clouds that strongly affect solar radiation forecasts. Different meteorological data sets, from point measurements to profile observations to gridded reanalysis and NWP model data, are used. Additionally, methods and algorithms have been created which enable research at scales varying from an individual measurement site to networks with hundreds of sites operating certain instruments, and to global scales.

Low-level jets

A low-level jet (LLJ) is a localized maximum in the vertical profile of horizontal wind. LLJs typically occur in the lowest few hundred meters of the atmosphere, therefore being potentially important for wind energy (Banta et al., 2013). The increased wind speed related to the LLJ maximum can enhance wind power production but on the other hand the increased wind shear and turbulence can be harmful for wind turbines. In addition, LLJs have other implications, such as their impact on the development of severe weather, transport of moisture and gases (Higgins et al., 1997; Mao and Talbot, 2004; Hu et al., 2013), therefore affecting air quality, as well as impacts on marine and aviation safety due to increased wind shear. There are different LLJ forcing mechanisms, such as inertial oscillation in time (Blackadar, 1957) and space (Högström and Smedman-Högström, 1984; Smedman et al., 1993), barrier and katabatic winds (Parish, 1982; Renfrew and S. Anderson, 2006), large scale baroclinicity, and shallow baroclinicity induced by the coastlines or sea-ice edges

(Doyle and Warner, 1993; Savijärvi et al., 2005). Different forcing mechanisms have different impacts on the occurrence and characteristics of LLJs.

Low-level jets have been studied widely over flat land areas, especially over the Great Plains in the United States where a nocturnal LLJ is a common phenomenon, especially in the summer season (Banta et al., 2002; Storm et al., 2009; Vanderwende et al., 2015). These LLJs are usually forced by an inertial oscillation in time when the boundary layer transforms from daytime unstable stratification to nighttime stable stratification, and the upper part of the boundary layer decouples from the surface resulting in decayed friction and accelerated horizontal wind speed in the boundary layer. However, LLJs can also occur in cold regions, although the forcing mechanisms may be different. LLJs have been studied in the Arctic (Moore and Renfrew, 2005) and in the Antarctic (Andreas et al., 2000; Renfrew and S. Anderson, 2006), but overall, there are fewer studies focusing on wintertime LLJs. This acknowledged imbalance is partly covered in this thesis by deriving the wintertime climatology of LLJs based on the reanalysis data.

Different types of meteorological data sets discussed in the previous section have been used in LLJ research. LLJs have been investigated with long time series of gridded model data, such as reanalysis data sets (Rife et al., 2010; Ranjha et al., 2013). Reanalysis data enable the research of the phenomena over large areas and over long time periods. NWP models may not represent the LLJs correctly, possibly due to their inaccurate representation of the stable boundary layer showing too much turbulent mixing (Storm et al., 2009; Floors et al., 2013), or too coarse vertical and horizontal resolution. Therefore, in order to understand the phenomena, to estimate the effects of the phenomena on wind power production, and to evaluate the model performance, it is important to investigate the phenomena by using different data. In this thesis, the climatology of LLJs is investigated by using regional renanalysis data and at two different sites based on long time series of Doppler lidar observations with high temporal and vertical resolution.

In recent years, the growing interest in wind energy has also raised interest in LLJs in coastal areas (Tucker et al., 2010; Pichugina et al., 2012; Dörenkämper et al., 2015; Peña et al., 2016). In wind energy applications, the focus area is the lowest few hundred metres above the ground and long data sets of wind profile observations are needed to investigate the climatology of LLJs. There are no previous climatological studies of LLJs in Finnish coastal regions. Accurate representation of LLJs can be obtained from high temporal and vertical resolution wind profile observations, and furthermore used to evaluate the ability of a numerical model to capture them. LLJs should be investigated at more sites to understand the forcing mechanisms and to extend the model verification. These aspects are partly addressed in this thesis by the algorithm development, and by using Doppler lidar observations for investigating LLJs in the

Finnish Archipelago and in Germany, as well as comparing results from the reanalysis data and LES model to the observed LLJs.

Clouds and cloud properties

A cloud consists of liquid droplets, ice particles, or both, suspended in the air. There are different types of clouds in the atmosphere. Traditionally clouds are divided into ten main groups that can be separated into low-, mid- and high-level clouds. Clouds are highly variable; cloud heights typically vary from ground level up to approximately 15 km in altitude, and, as can be visually observed, have different sizes, shapes and structures, and vary in transparency. The cloud forcing mechanisms and atmospheric conditions determine the cloud properties.

As clouds consist of liquid and/or solid particles, the cloud optical properties highly depend on the constituents of a cloud. High clouds typically consist of ice particles only, being optically thinner than mixed-phase clouds or liquid clouds, that contain liquid droplets. Mixed-phase clouds contain a mixture of ice and supercooled droplets at temperatures below freezing, down to $-40°$C. For the same amount of water content ice clouds, mixed-phase clouds and pure liquid clouds show different optical properties, as ice particles are usually larger than liquid cloud droplets (Korolev et al., 2017).

NWP models forecast the cloud liquid/ice water contents at every model level for each grid point, from which the cloud fraction information at each grid point can be obtained. The single-level values of cloud cover for each layer (low, mid, high) as well as total cloud cover are derived from the forecast cloud liquid/ice water contents over the each layer and each model column. NWP models derive the cloud optical properties from the cloud liquid water and cloud ice water contents in each grid point. From these variables the cloud liquid water path and cloud ice water paths can be estimated, describing the total amount of cloud liquid and cloud ice water contents in one column. Extensive cloud profiling measurement stations are sparsely located, and therefore the comprehensive evaluation of a model's skill in predicting clouds is only done at a few ground-based sites (Illingworth et al., 2007; Hogan et al., 2009) or from profiling satellites which have a very narrow swath (Delanoë et al., 2011). Therefore, there is a shortage of research evaluating model's skill in predicting clouds against high temporal resolution observations. In this thesis, this need is partly covered by using ceilometer observations, which are densely distributed globally.

Forecasting solar radiation and clouds

In the solar energy field, the interest is in the actual and forecast amount of solar radiation on the ground. The solar radiation received at the Earth's surface depends on the solar zenith angle and the absorption and scattering of the radiation in the atmosphere, clouds being the major contributor. Both the amount of clouds (cloudiness) and cloud type affect the amount of solar radiation reaching the surface: optically thick liquid clouds scatter solar radiation more effectively than deeper but optically thinner ice clouds, resulting in less solar radiation on the ground when liquid or mixed-phase clouds are present. Operational NWP models can be used to predict the incoming solar radiation and to estimate the potential solar energy produced by the solar farm, for example, one day-ahead. The model's capability to predict the incoming solar radiation is dependent on the model's capability to predict clouds. Numerical models have been shown to have deficiencies in predicting clouds containing supercooled liquid (Forbes and Ahlgrimm, 2014) resulting in a bias in the predicted shortwave solar radiation (Ahlgrimm and Forbes, 2012).

There are earlier studies estimating the accuracy of the solar radiation forecasts (e.g. Schroedter-Homscheidt et al., 2017) and accuracy of the solar radiation data obtained from the reanalysis (e.g. Frank et al., 2018; Urraca et al., 2018) at different locations based on solar radiation measurements, satellite-derived radiation products and numerical model data. These studies focus on solar radiation forecast error, and do not investigate the possible source of the error. Investigating the impact of the representation of clouds in NWP models on solar radiation forecasts mainly rely on extensive cloud profiling instrumentation (Ahlgrimm and Forbes, 2012), that are installed at sparsely distributed research facilities, such as Cloudnet stations (Illingworth et al., 2007) and Atmospheric Radiation Measurement facilities (Mather and Voyles, 2013). In this thesis, the emphasis has been to step beyond solely documenting accuracy of the solar radiation forecast and investigating the impact of low- and mid-level clouds by using simpler instrumentation, therefore being applicable to hundreds of sites globally.

3. Data and methods

In this thesis, a wide range of different meteorological data were used to identify and model LLJs, and to observe and forecast clouds and solar radiation. Vertical profiles of horizontal wind speed obtained from reanalysis data, Doppler wind lidar observations and an LES model were used to investigate LLJs. In addition, wind speed measurements from cup and sonic anemometers, and radiosoundings were used as an additional source of wind speed information. Clouds and solar radiation were observed using ceilometer and pyranometer instruments, respectively, and forecast by the operational NWP model. Automated algorithms were developed to objectively identify LLJs and the presence of clouds. The specific observational data sets, numerical model data and algorithms used in this thesis are described in the following sections in more detail.

3.1. Observational data

Doppler lidar observations

Doppler lidar observations are used in papers II and III to obtain vertical profiles of horizontal wind speed and direction and to investigate LLJs. A Halo Photonics Streamline Doppler lidar is used in both studies (Pearson et al., 2009). This instrument emits a light pulse at a wavelength of 1.5 μm and measures the Doppler shift of the backscattered signal, which is further post-processed to get the line-of-sight velocity of the air (aerosols). Furthermore, the wind speed and direction profiles are calculated from the combination of the line-of-sight velocities in several beam directions, assuming the horizontal homogeneity of the wind field. The line-of-sight resolution is 30 m, and therefore changing the scanning pattern of the instrument (and the elevation angle of the beam) changes both the vertical resolution of the final wind profile and also the measurement volume over which horizontal homogeneity must be assumed. In addition, the temporal resolution of the wind measurements depends on the choice of the scanning pattern.

In paper II, the temporal resolution of the wind profiles is 10 minutes, and the wind profile is concatenated by using two different scanning types, a 24-beam VAD scan at 4°elevation and a 3-beam DBS scan at 70°elevation, and additional sonic anemometer observations. The resulting vertical resolution is 2 m below 130 m, where the VAD scan is used and 28 m above 130 m, where the DBS scan is used. Sonic anemometer measurements were inserted at the corresponding height level (20 m above ground). The vertically pointing operation between the two different scans was used to derive the vertical velocity.

In paper III, the scan type used was a VAD at 75°elevation angle, resulting in vertical a resolution of 29 m. The temporal resolution of the data was 15 minutes. Over two years of continuous Doppler lidar observations were used in paper II, and in paper III the data period was over four years.

Ceilometer observations

Four years of continuous Vaisala CL51 ceilometer atteanuated backscatter profiles were used in paper IV to detect clouds. The ceilometer emits a laser pulse close to 910 nm into the atmosphere and receives the backscattered signal from the aerosols, cloud droplets and precipitation. The backscatter coefficient is reported with 10 m range resolution up to 15 km, with a vertical profile every 15 seconds. The knowledge of the shape of the attenuated backscatter profiles and the magnitude of the attenuated backscatter coefficient in cases of clear sky, liquid cloud layer, ice cloud, precipitation, and fog can be used to identify these meteorological conditions automatically from the ceilometer data. The laser signal attenuates in thick cloud layers or in heavy precipitation, and no information is available from above. However, the ceilometer time series data can be used to estimate the amount of clouds in the sky (cloudiness).

Other observations

In addition to ground-based remote sensing instrumentation used in papers II, III, and IV, more traditional meteorological observations were used. Additional wind observations in papers II and III were obtained by using sonic anemometer, cup anemometer and wind vanes. These observations were used to supplement the Doppler lidar wind speed measurements and to quality check the Doppler lidar data. Data from radiosoundings are used in paper III to compare the results of a case study. Eddy-Covariance technique, used in paper III to investigate the effect of LLJs on the fluxes of latent and sensible heat and the net ecosystem CO_2 exchange, requires a sonic anemometer in addition to an open path gas-analyser (Mauder et al., 2013). Pyranometers were used in paper IV to observe the GHI, and 1-minute averaged, quality-controlled GHI values (Long and Shi, 2008; Rontu and Lindfors, 2018) over four years were used.

3.2. Model data

Arctic System Reanalysis

The first version of the Arctic System Reanalysis (ASR) data set (ASR-Interim, Bromwich et al., 2010) was used in paper I to investigate the climatology of LLJs. ASR covers Northern hemisphere mid-latitude and polar regions north of

45°N. ASR is optimised for polar regions as it was produced by using the polar optimised Weather Research and Forecast (Polar-WRF) model with three-dimensional variational (3D-Var) data assimilation scheme. The horizontal resolution is 30 km, and the model has 71 model levels. The output data were available at 34 pressure levels resulting in a vertical resolution of 25 hPa between 1000 hPa and 500 hPa. Temporal resolution of the reanalysis output was three hours. The downloaded variables contained horizontal wind components (u, v) and geopotential height at each model pressure level, in addition to single-level parameters such as terrain height and wind components at 10 m height. The data set used covered winter season (October to March) over an 11-year period (2000 to 2010).

Integrated Forecast System

Integrated Forecast System (IFS) is a global forecast model run operationally by the European Centre for Medium-Range Weather Forecasts (ECMWF). IFS model output was used in paper IV to investigate the cloud and solar radiation forecasts. The high-resolution deterministic forecasts are run every 12 hours and forecasts up to 10-day-ahead are produced. The horizontal resolution of the latest model cycle is approximately 9 km and there are 137 vertical levels. The vertical grid spacing is denser closer to the ground. In this thesis only data below 15 km is considered (as we are interested in clouds) and therefore the vertical resolution varies between 20 and 300 m. The temporal resolution of the model output is one hour. For the model evaluation, only the closest grid point to the measurement site is considered and day-ahead forecasts (initialisation at 12 UTC, forecast hours T+12 to T+35) were used to represent each day from 00 UTC to 23 UTC. The day-ahead cloud and solar radiation forecasts were evaluated over a four year time period (2014–2017) by using the single-level cloud cover and solar radiation fields (low cloud cover, medium cloud cover, downward surface solar radiation). In addition, other single-level and model-level fields were downloaded and used in paper IV for more detailed analysis, for example, the temperature and specific cloud liquid water content fields for investigating the solar radiation forecast error in case of supercooled liquid clouds vs. warm liquid clouds. A full documentation of the IFS can be found from ECMWF documentation (ECMWF, 2019, https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model/ifs-documentation (last access: 1 April 2019)).

ICON Large Eddy Model

The global ICOsahedral Non-hydrostatic atmospheric model (ICON, Zängl et al., 2015) is developed further to perform as a large eddy simulation model (ICOM-LEM, Dipankar et al., 2015) and evaluated by Heinze et al. (2017). In paper III, LES simulation of one day, produced by using ICON-LEM, is used in a case study to investigate the spatial representation of the wind field around Jülich Observatory for Cloud Evolution measurement site, in Jülich, Germany. The model setup, similar to that used by Heinze et al. (2017), includes four nests starting with the outermost nest with a radius of 110 km and a horizontal resolution of 624 m to the innermost nest with a radius of 10 km and a horizontal resolution of 78 m, centered at the measurement site. There are 33 vertical levels in the lowest 2 km, resulting in minimal layer thickness of 20 m. The model output is stored every 10 minutes over the whole domain, and profile data every 9 seconds at the measurement site are available.

3.3. Algorithm development

Different algorithms have been developed in this thesis to automatically investigate the phenomena of interest. A LLJ identification algorithm suitable for a gridded data set was created in paper I to investigate the LLJs grid point by grid point. In paper II, a LLJ identification algorithm suitable for high temporal and vertical resolution wind profile data from Doppler wind lidar was created and applied to over two and over four years of wind profile data in papers II and III, respectively. Cloud detection was produced by the combination of three algorithms: detection of liquid layer, precipitation and fog, which were developed in paper IV.

Low-level jet identification

A low-level jet is a local maximum in the vertical profile of the wind speed. In paper I, the following approach is used to identify LLJs from the reanalysis data: First, the heights and wind speeds of all local maxima and minima below 1500 m are identified (Figure 1). It is further required that the local maximum must fulfill the criteria of being at least 2 m s^{-1} and 25 % stronger than the local minima above and below the maximum, following the criteria by Baas et al. (2009), to be identified as a LLJ feature. Multiple LLJs are allowed and identified with the algorithm, if present. In paper I, this approach is applied to all time steps (every 3 hours) and for each grid point to identify LLJs automatically from the ASR data.

In paper II, in addition to the identification described above, additional steps are required for LLJ identification in high temporal and vertical resolution Doppler lidar data. It is required that the identified LLJ is a coherent feature and therefore each wind profile is compared to the previous profile requiring that there are no sudden jumps in the wind speed values, for example due to data quality issues. Additionally, it is required that the feature is present for at least one hour, discarding individual profiles to be identified as LLJ case. This approach is then applied to all wind profile

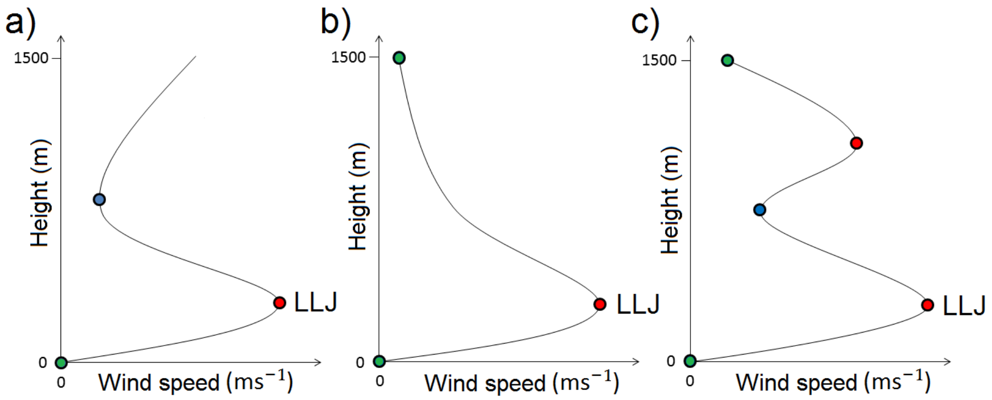

Figure 1: Schematic figure of identification of a LLJ from a wind profile. Red dots show local maxima, blue dots show local minima and green dots show points where minima are declared due to their location either at the surface or immediately below 1500 m. (a) The case of one local maximum and one local minimum below 1500 m, (b) the case of one local maximum but no local minimum below 1500 m and (c) the case of two local maxima and one local minimum below 1500 m. Figure from paper I, © 2015 The Atmospheric Science Letters

measurements from the Doppler lidar data automatically. The algorithm can be also applied to real-time Doppler lidar measurements to operationally identify LLJs.

Fog, liquid cloud layer and precipitation identification

Attenuated backscatter profile from the ceilometer reveals information on the meteorological conditions, such as whether it is precipitating or not. It also gives information on clouds, whether there is fog, liquid cloud layers or high ice clouds. These conditions can be automatically identified based on the shape of the attenuated backscatter profile and the magnitude of the signal.

A fog layer just above the ground shows a strong attenuated backscatter signal in the first range gates with rapid decrease above, as the lidar signal is attenuated in the fog layer (Figure 2a). Liquid cloud layers above the surface show a similar feature, however the full peak shape is visible (Figure 2b). The shape of the attenuated backscatter signal is different in the case of precipitation, as the the lidar signal is not attenuating as fast as in liquid clouds and the lidar can "see" further into the layer resulting in wider and weaker peak (Figure 2c). These principles of the physical behavior of the transmitted laser pulse and the received backscattered signal can be used to automatically detect these meteorological conditions.

These algorithms can be used for both research and operational purposes. In addition to derive the cloudiness, the accurate real-time detection of liquid cloud layers can be crucial for wind turbine operation as in-cloud icing due to clouds containing supercooled liquid is a notable issue in cold climates.

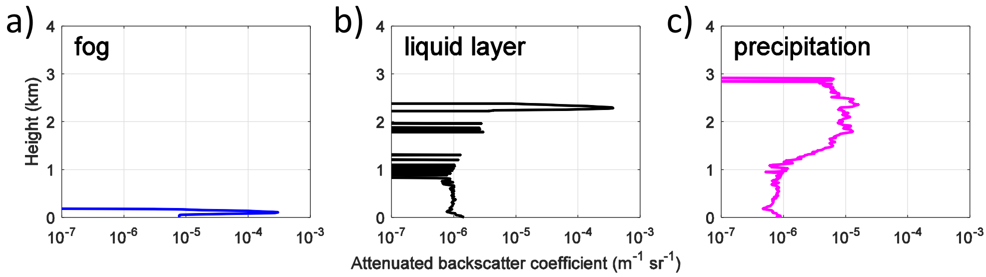

Figure 2: Schematic figure of identification of a) fog, b) liquid layer and c) precipitation from ceilometer attenuated backscatter profile data. Figure from paper IV, © 2019 Atmospheric Chemistry and Physics

4. Overview of main results

4.1. Climatology of wintertime low-level jets based on Arctic System Reanalysis

An 11-year climatology of low-level jets occurring in winter-time (October to March) in the Northern hemisphere mid-latitudes and polar regions was developed based on the Arctic System Reanalysis data set in paper I. A LLJ identification algorithm was created and applied to wind profiles obtained from the reanalysis at every time step and grid point. The LLJ frequency of occurrence and characteristics, the mean LLJ wind speed and height, were determined. These LLJ properties depend upon a range of geographical influences, including topography and contrasts in surface roughness and temperature across land/ocean and sea ice/open ocean boundaries.

The highest LLJ frequency of occurrence (up to 80–90%) was found to be associated with strong gradients in topography: on the coasts of Greenland and in the south-eastern parts of Russia where, based on the analysis of LLJ characteristics, LLJs are most probably due to katabatic forcing. High LLJ occurrences were also found elsewhere in the mountainous areas in Siberia and Alaska. In general, a higher LLJ frequency of occurrence was found over land compared to open sea. However, over sea ice the LLJ frequency of occurrence is higher compared to open sea. High LLJ frequency of occurrence values were found to be located on the sea-ice edge area where the strongest baroclinic zone between the open sea and sea ice is present.

The sea-ice effect was investigated further and Figure 3 shows that the higher LLJ occurrence values follow the sea ice edge (red line). During March (Figure 3a), when the sea ice cover over the Arctic is at its maximum, the LLJ occurrence is high especially over sea ice near the ice edge. In October (Figure 3b), when the sea ice cover is at its minimum, the LLJ occurrence is lower over those areas where the sea ice edge enhanced the LLJ occurrence in March but from where the sea ice has retreated towards north in October. The LLJ occurrence over steep topographical gradients, such as over Greenland, remains high in both cases and a LLJ feature is present over 80% of the time, therefore strengthening the hypothesis of topography-related forcing mechanisms playing an important role.

The strongest and highest LLJs, in terms of wind speed maximum and its altitude, occurred over the open sea, however this is where the LLJ occurrence is relatively low. The spatial variation of the mean height of LLJ reveals that in some areas LLJs always occur very close to the ground, such as in the coastal regions of Greenland and in the mountainous areas in Siberia and Alaska – from where no previous LLJ studies are available. In these areas the mean height of LLJs was below 200 m. These low, but frequently occurring LLJs show LLJ mean wind speeds of up to 14 $\mathrm{m\,s^{-1}}$.

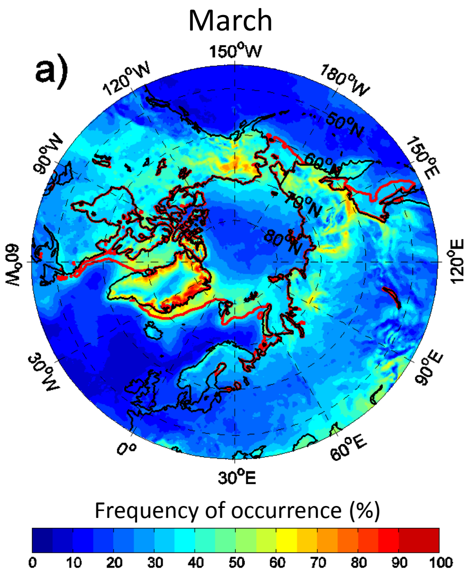

Figure 3: The low-level jet frequency of occurrence in (a) March when the sea ice has its maximum extent and (b) October when the sea ice has its minimum extent. The sea-ice edge, defined as the 11-year mean sea-ice concentration greater than 0.5 is shown by the red contour. Figure from paper I, © 2015 The Atmospheric Science Letters.

The use of a reanalysis dataset enabled the investigation of LLJs over a long time window and over a large area, revealing previously unknown areas of high LLJ occurrence. On the other hand, there are deficiencies in temporal and spatial resolution of the reanalysis data increasing the uncertainty of the results. In this study, only wind profiles below 1500 m were investigated. The vertical resolution of the reanalysis output results in 8 to 9 vertical levels below 1500 m, thus resulting in coarse representation of the boundary layer. The coarse vertical resolution in addition to 3-hourly temporal resolution of the output affects the results and the finest structures and rapid changes of the stable boundary layer and the LLJs may not be well captured. Therefore, the importance of high temporal and vertical resolution data are well acknowledged as an additional source of data to verify the reanalysis results.

4.2. Climatology of low-level jets based on Doppler wind lidar observations

Low-level jet climatologies, obtained based on Doppler lidar wind profile observations, were derived at Utö, Finland in paper II and at Jülich, Germany in paper III. A LLJ identification algorithm suitable for high temporal and vertical resolution Doppler lidar data was created in paper II and applied to several years of wind profile observations from Utö and Jülich. With long time series of high temporal and vertical resolution wind profile observations, the LLJ frequency of occurrence and LLJ characteristics were derived with greater detail for specific sites than what was possible to achieve based on the reanalysis data in paper I.

Figure 4 shows two examples of the Doppler lidar wind data measured at Utö, Finland, with the LLJ identification algorithm applied to the measured wind profiles (black stars denoting a detected LLJ case). The data availability issues of the Doppler lidar data due to clean air (lack of aerosols to track, especially an issue at Utö), the presence of low clouds (fully attenuated lidar signal) and turbulent motions (invalid horizontal homogeneity assumption) may affect the results, as at times the wind data must be discarded as unreliable (Figure 4b). However, the Doppler lidar is a powerful instrument to obtain wind profiles in the lowest few hundred meters of the atmosphere, at height levels specifically important to wind energy. The low-level jet identification algorithm created in this study is also suitable for operational use, and the algorithm has already been applied to other Doppler lidars, both for research and operational use.

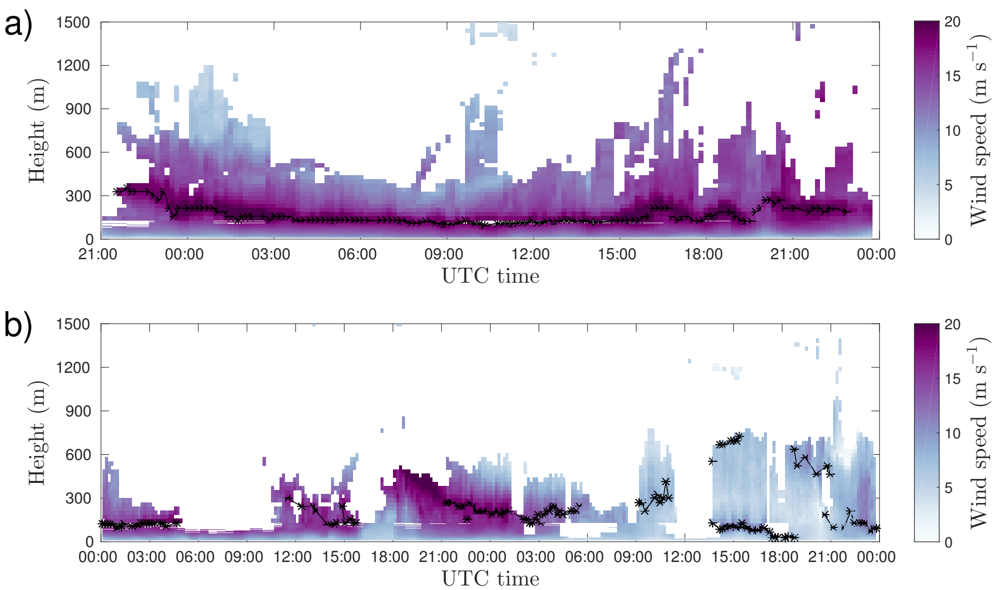

Figure 4: Time–height plots of horizontal wind speed derived from Doppler lidar data at Utö (a) between 2100 UTC 20 May 2013 and 0000 UTC 22 May 2013 and (b) between 17 and 18 May 2013. Horizontal wind speed is given by the color shades; white regions denote missing wind speed data due to lack of signal. Black stars denote LLJ profiles, with black lines linking appropriate LLJ profiles into an LLJ case. Figure from paper III, © 2017 American Meteorological Society

Utö is a small island in Finnish archipelago, and the area could be a potential source of wind energy production in the future. LLJs are a common feature at the site, the mean LLJ frequency of occurrence over all seasons being 12%. A clear seasonal cycle is observed at Utö with LLJ frequency of occurrence less than 5% in winter, and up to 30% during summer. However, there is only a slight increase in LLJ occurrence at nighttime in summer, and apart from that no clear diurnal cycle was observed. In turn, some jets were found to persist continuously over several days. The mean LLJ wind speed is 11.6 $\mathrm{m\,s^{-1}}$ and the strongest LLJs are observed during spring and winter. The majority of the LLJs were observed below 150 m in all seasons, thus can have a major impact of wind turbine operations. Additionally important for wind energy, the wind shear induced by the LLJs due to the strong change in wind speed with height was found to be greater below the jet compared to above the jet.

By using the same LLJ identification algorithm as in paper II, a climatology of LLJs was derived at Jülich, Germany, and similar statistics of LLJ characteristics were derived. LLJ occurrence shows a much clearer diurnal cycle at this location, compared to results from Utö, strongly favoring nighttime occurrence. The locations of these two sites highly affect the results; Utö is located in the archipelago representing marine conditions, whereas Jülich represents a continental site and is located further south. Therefore, the forcing mechanisms and characteristics of the LLJs in these two locations would be expected to differ. In paper III the shear and turbulence characteristics of LLJs and their influence on the surface fluxes were investigated based on the additional surface measurements. Similarly, as found in paper II, the wind shear is highest below the jet, and it was shown in paper III that the turbulence connected to the jet is high close to the ground. This is highly important for wind energy, as the highest shear and turbulence values related to the LLJs are occurring at low altitudes, within the height range of modern wind turbines.

A case study utilizing an LES model in paper III showed that the LES model captures the LLJ feature, however, the modeled LLJ has slightly stronger and sharper LLJ maximum in the wind speed profiles compared to the Doppler lidar observations, potentially due to too weak turbulent mixing in the model. The LES model was used to further understand the effect of topography to the wind field. The analysis revealed that the small hill close to the measurement site can affect the spatial wind field.

4.3. Evaluating cloud and solar radiation forecasts

Operational one day-ahead cloud and solar radiation forecasts by the ECMWF IFS model were evaluated at Helsinki, Finland, by comparing ceilometer and solar radiation observations to cloud cover and solar radiation forecasts in paper IV. Algorithms to detect liquid cloud layers, fog, and precipitation from ceilometer attenuated backscatter profiles were developed to obtain reliable cloud cover information (Figure 5). In addition, methods to enable a fair comparison between model forecasts and point observations were developed and tested at one site in this study.

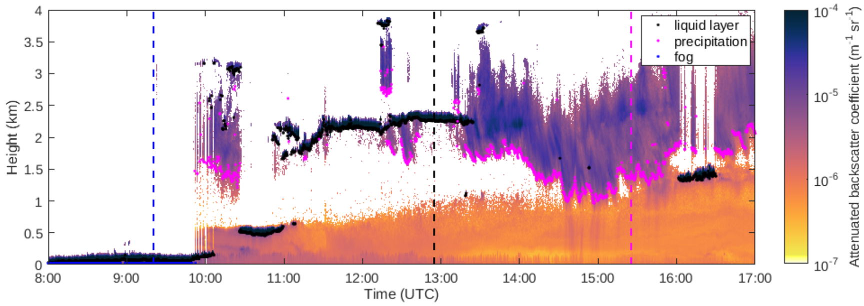

Figure 5: Time–height cross section of attenuated backscatter profiles from a Vaisala CL51 ceilometer on 30 March 2016 at Helsinki, Finland. Overplotted are the results from our identification algorithms: fog (blue dots), liquid cloud base (black dots), and precipitation base (magenta dots). The dashed lines represent the time steps of the sample attenuated backscatter profiles shown in Figure 2. Figure from paper IV, © 2019 Atmospheric Chemistry and Physics.

The skill in forecasting clouds was found to be lower in spring and summer when there are more broken cloud cases compared to winter when overcast situations are more common and easier to predict. However, in summer the amount of incoming solar radiation is highest due to the seasonal cycle of solar radiation, originating from the seasonal cycles of the solar zenith angle and cloudiness.

At Helsinki, Finland, the solar radiation forecasts show overall positive bias. In principle, the bias is negative in cases where the model overestimates the cloud cover (cases above the diagonal in Figure 6) and positive when the model underestimates the cloud cover (cases below the diagonal in Figure 6). A negative bias was found in clear cases where the cloud cover was correctly forecast (lower left corners in Figure 6) and a positive bias was found in overcast cases where the cloud cover was correctly forecast (upper right corners in Figure 6).

Averaging the data from hourly to 3-, 6-, 12-hourly, and daily values, the skill in cloud cover forecasts increased and solar radiation forecast errors decreased with increasing averaging window. This is an important finding as it shows that the model performs better when estimating the cloudiness and the amount of solar radiation over a longer time window, as it is difficult for the model to get the exact timing of the clouds correct with hourly temporal resolution at one specific location. This result suggests that the model performs better in getting the cloudiness and the amount of solar radiation correct on average, rather than predicting each individual cloud accurately.

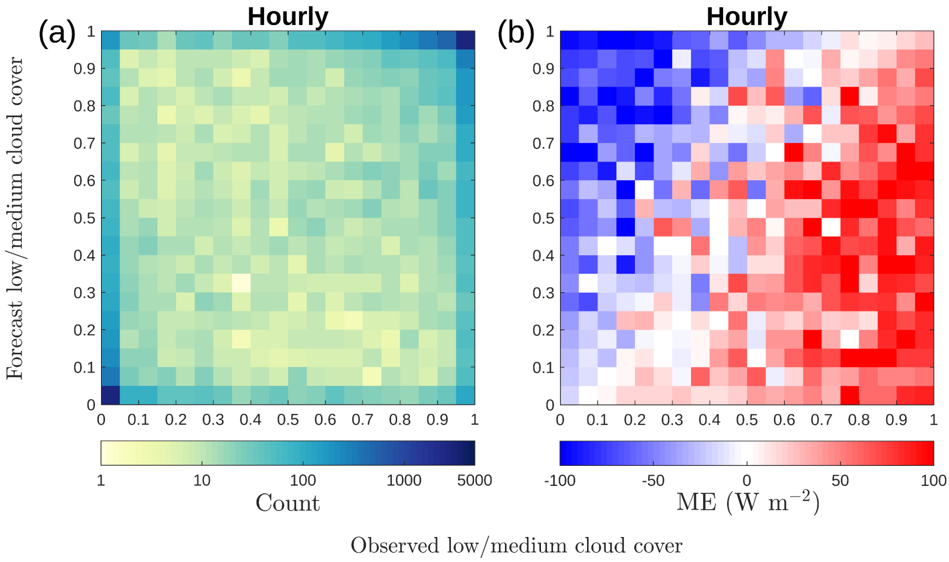

Figure 6: 2D-histogram of (a) observed and forecast cloud cover, with colors representing counts on a logarithmic scale, and (b) Mean error (ME) in solar radiation forecast for each cloud cover pair in (a). Figure from paper IV, © 2019 Atmospheric Chemistry and Physics.

The positive bias during correctly forecast overcast cases was investigated further and found to be related to cases where the forecast cloud Liquid Water Path (LWP) is low. These results suggest that the model is either not producing enough cloud liquid water or that there are deficiencies in forecasting the optical properties of clouds having low LWP. This aspect should be investigated further with LWP observations that were not available for this study at this site.

The algorithms and methods developed in this study can be further applied to hundreds of sites globally to investigate the skill in cloud and solar radiation forecasts based on relatively simple data sets. The liquid layer identification algorithm can be also used in the wind energy sector to estimate the conditions of in-cloud icing, as supercooled liquid clouds play an important role in case of meteorological icing of wind turbine structures.

5. Review of papers and author's contribution

Paper I: The focus of this study was to determine the climatology of LLJs in the mid-latitudes and polar regions of the Northern Hemisphere based on reanalysis. The focus was on the cold season (October to March) and the aim was to investigate where LLJs frequently occur and what are their mean characteristics.

Paper II: The first aim of this study was to develop an objective LLJ identification algorithm suitable for Doppler wind lidar and the second aim was to apply the algorithm over two years of wind profile measurements from Utö, Finland, and to investigate the LLJ occurrence and characteristics, and their seasonal and diurnal variability.

Paper III: The objective of this study was to investigate LLJ occurrence and characteristics, and their seasonal and diurnal variability at Jülich, Germany based on Doppler lidar observations. A more detailed analysis on the LLJ turbulence characteristics and the influence on LLJs on the surface fluxes was conducted in addition to a case study focusing on the interaction of a LLJ with the local topography.

Paper IV: The objective of this study was to investigate how well clouds and solar radiation are forecast at Helsinki, Finland, based on ceilometer and pyranometer observations and operational NWP model output. The aim was to develop fast and robust methods for investigating the relation between cloud and solar radiation forecasts, which can then be applied to hundreds of sites globally by using relatively simple instrumentation.

The author was responsible for most of the work in **papers I**, **II** and **IV**. For **paper I**, the author developed the low-level jet identification algorithm, applied it to the gridded reanalysis data, post-processed and analysed the results, and wrote the paper with the help of co-authors. For **paper II** the author developed an automated low-level jet identification algorithm, applied the algorithm to Doppler wind lidar observations, analysed the results, and wrote the manuscript with the help of co-authors. The low-level jet identification algorithm suitable for Doppler lidar data was further implemented to another site with a Doppler lidar, and the results are shown in **paper III**. The author helped with implementing the algorithm, analysing the results and writing the manuscript. The algorithm development, analysis of the results and writing of **paper IV** was mostly done by the author.

6. Conclusions and future perspectives

How can low-level jets and clouds, and their potential impact on renewable energy, be investigated based on a range of meteorological observations, reanalysis and numerical weather prediction model output?

An 11-year wintertime climatology of LLJs was investigated in **paper I** based on the reanalysis data set covering the Northern Hemisphere mid-latitude and polar regions. The occurrence of LLJs and their mean characteristics were investigated and new information on frequently occurring LLJs was gained in regions where no earlier LLJ studies have been conducted. Reanalysis data can be used to increase our understanding of certain phenomena over a wider temporal and spatial scale to understand the "bigger picture". This information is helpful for example when prospecting potential areas for renewable energy production before any detailed analysis.

More detailed climatologies and characteristics of LLJs at individual sites are derived in **papers II** and **III** based on long-term Doppler wind lidar observations. Site specific information on the shear and turbulence characteristics related to LLJs can be investigated with high temporal and vertical resolution Doppler lidar data. This information can be further utilized in understanding how LLJs would affect structures, such as causing stress on the wind turbines.

A climatology of cloudiness and solar radiation at Helsinki, Finland was derived in **paper IV** based on ceilometer and pyranometer observations. The skill in operational short term (day-ahead) cloud forecast and its impacts on solar radiation forecast were evaluated by using fast and simple methods developed in this paper. These methods are applicable for any site with relatively simple instumentation: ceilometer and pyranometer observations. Therefore, this study can be repeated at hundreds of sites globally, a major advantage compared to the previous studies, conducted mainly at a few measurement sites having extensive research instrumentation.

The algorithms created in this thesis enable the real-time identification of LLJs and clouds, separating liquid cloud layers, precipitation (and ice clouds) and fog. These algorithms are available for operational and research purposes, and they are applicable to Doppler lidar wind profiles and ceilometer attenuated backscatter observations. The LLJ identification algorithm has been applied to different studies and is in operational use at the Mace Head station operated by the National University of Ireland Galway. The liquid cloud layer identification will be applied to the European-wide cloud profiling network, Cloudnet, and the European-wide ceilometer network, E-Profile, enabling the detection of liquid clouds more accurately than previously achieved. The improved cloud detection algorithms are already used operationally at the Finnish Meteorological Institute. The algorithms for ceilometer data can be also used to identify potential icing conditions that are important for aviation and wind energy.

How well do different numerical models represent low-level jets, clouds and solar radiation?

Results of LLJs derived based on reanalysis data in **paper I** were compared to results from one specific site in **paper II** by investigating the closest grid point to the measurement site. The LLJs identified based on reanalysis were higher and weaker than those observed with the Doppler lidar, but the predominant LLJ direction was similar in both data sets. Thus, there are deficiencies in the ability of reanalysis to represent this phenomenon accurately, probably due to the coarse spatial and temporal resolution. For example, at Utö, the LLJ can occur in the lowest 50 meters, and therefore it is challenging for the model to represent such rapid changes in the vertical if the model vertical resolution is quite coarse.

In **paper III**, an LES model was used to investigate the effect of topography on a LLJ case. In this study, it was seen that this individual case was quite well represented in the model. However, the LES model may not help with operational use, because of the high computational requirements for achieving the necessary resolution. Running the LES model is computationally expensive and therefore not suited for operational use. However, the detailed analysis of LLJ forcing mechanisms with LES models increases our understanding of the phenomenon, and these methods should be extended in the future to other sites.

In **paper IV**, the conclusions of the evaluation of an operational NWP model's skill in forecasting clouds and solar radiation revealed that the model predicts clouds and solar radiation quite well on average. However, there are difficulties in forecasting the timing of clouds, resulting in large errors, especially for hourly values. The model shows a positive bias in overcast situations, which is attributed to a problem in representing cloud properties, resulting in an inaccurate solar radiation forecast even though the amount of cloud is correctly forecast. Additionally, it was found that the model shows a negative bias in cloud-free situations, potentially due to deficiencies in representing the aerosols. The results in this study should be repeated at several sites to gain more understanding of these errors.

How observational systems can help numerical weather prediction model development?

This thesis includes algorithm development that can help both NWP model and furthermore reanalysis development. The LLJ identification algorithm developed in **paper II** can be applied to any site having Doppler lidar. To understand the model capability in representing LLJs, long data sets of observational data can be investigated by applying the objective LLJ identification algorithm and consistently comparing the results with the model output. The characteristics of LLJs can be compared between the model and observations to understand which aspects the model can represent, and which ones it fails to capture in different conditions. Similarly, reanalysis data can be evaluated in more detail to gain information on when the reanalysis accurately captures observed features.

The methods in **paper III** using LES model to reproduce the LLJ feature can help model development as more information can be gained on the effects of changing model parameters or parametrizations, and model resolution. This enables more information on the model's capability to produce the phenomenon and can help us to understand what features are the most critical when interested in LLJs.

The methods in **paper IV** can guide model physical process development as potential root causes for errors in solar radiation forecasts were identified. More analysis should be made in order to get reliable results, for example, including observations of LWP. Additionally, more sites should be included in the analysis to understand if similar features can be seen elsewhere giving more confidence on the causes of errors.

In the future, more analysis on the model's performance regarding LLJs, clouds and solar radiation can be achieved with the algorithms and methods developed in this thesis. Attention has to be paid to get comparable data sets between the observations and model output due to the fundamental differences in point observations and gridded model data, as described in more detail in **paper IV**.

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